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A SILICON DETECTOR READOUT SYSTEM USING COMMERCIALLY AVAILABLE ITEMS

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A. Physics of Silicon Detectors

The properties of silicon microstrip detectors (SMD) have been extensively reviewed elsewhere[1]. In this note the basic properties are briefly noted.

1) Bulk Properties

The Einstein relation between the diffusion coefficient D and the mobility μ is:

$$kT = qD/\mu \qquad 1)$$

where q is the electron charge, and kT is proportional to the thermal energy. For silicon the electron mobility is $\mu_e \sim 1400$ $cm^2/V.sec$ while the hole mobility is $\mu_h \sim 500$ $cm^2/V.sec$. The energy gap is $Eg=1.12$ eV. The intrinsic density of charge carriers at 300^oK is $n_i \sim 10^{11} cm^{-3}$. The doped conductivity obeys $n_i p_i = np$, which for typical doping yields a resistivity ρ (related to charge q, mobility μ, and density n)

$$\rho = 1/q\mu n \qquad 2)$$

of $\rho_i \sim 200$ K Ω.cm, $\rho_n \sim 20$ K Ω.cm.

Charge is typically collected over a depletion depth $d=300$ μm. The density of Si is 2.33 gm/cm^3, and the radiation length x_o is 9.36 cm. A depth of 300 μm is 6.6×10^{-4} of an interaction length λ_I, 3×10^{-3} of x_o, and causes an energy loss of 116 keV. The energy to liberate a pair is 3.62 eV which means 32,000 pairs in 300 μm or 5.1 fC of charge, Q_s, to collect.

2) Electrical Properties

The dielectric constant of Si is $\epsilon=1.05$ pf/cm or 11.9 ϵ_o. The relationship between V and I at a junction is

$$I(V) = I_o(e^{qV/kT}-1) \qquad 3)$$

From this relation the forward junction resistance is $R_F=(dI/dV)^{-1} = kT/qI$. For 300^oK at I=1 ma, then $R_F=25\Omega$. The reverse current I_o is difficult to calculate from first principles.

Application of a reverse voltage V_D to the junction results in a depletion region containing only fixed ions. The extent of this region can be calculated using electrostatics; $\vec{\nabla}.\vec{E} = \rho/\varepsilon = dE/dz = qn/\varepsilon$. Then $E=(qn/\varepsilon)z$ and since $\vec{E}= -(\vec{\nabla}V)= -dV/dz$, $V=qnz^2/2\varepsilon$. For a depletion voltage V_D

$$V_D = \frac{qnz_D^{\,2}}{2\varepsilon} = z_D^{\,2}/2\varepsilon\rho\mu \qquad 4)$$

For example, full depletion $d=z_D=300$ µm requires, (if $\rho=6$ KΩ.cm, $\mu=\mu_e$) that $V_D=51$ V. The capacity of this depletion region per unit area is ~ ε/z_D. For $z_D=d$, ε/d is 35 pf/cm^2. A strip of 50 µm pitch 5 cm long has a source capacity C_s ~ 0.9 pf. Thus the source capacity is small for silicon strip detectors and is dominated by stray input lead capacity.

3) Longitudinal Charge Collection

Suppose the detector is fully depleted, then $z_D = d$ or $V_D = d^2/2\varepsilon\rho\mu$. In this case

$$E(z) = \left(\frac{2V_D}{d^2}\right) z \qquad 5)$$

The velocity of charge motion is $dz/dt=\mu E(z)$. Integrating this equation of motion

$$z(t) = d\, e^{-t/t_c} \qquad 6)$$

where the charge collection time t_c is

$$t_c = (d^2/2V_D\mu) \qquad 7)$$

This equation can be thought of crudely as motion in a field ~ V_D/d of ~ 3.3 kV/cm. The velocity is roughly ~ $(V_D/d)\mu$ ~ 4.7×10^6 cm/sec. Over a distance ~ d/2 the electron charge is collected in a time t_c ~$(d/2)/(V_D/d)\mu$ ~ 3.2 nsec.

Assuming uniform ionization deposition, the collected charge and current go as

$$i(t) = \frac{Q_s}{t_c}\, e^{-t/t_c} \qquad 8)$$

$$Q(t) = Q_s(1-e^{-t/t_c}) \tag{9}$$

For Q_s=5.1 fC and t_c=9.0 nsec (holes), the initial hole current is $i(o)=Q_s/t_c$=0.57 μA.

4) Transverse Charge Collection

During drift toward the pickup electrode, the charge carriers diffuse. The distribution in a transverse coordinate y is gaussian with rms.

$$\sigma_y \simeq \sqrt{2D_h t} \tag{10}$$

As a rough approximation, using $t \sim t_c$ and equation 1 for D,

$$\sigma_y \sim d \sqrt{\frac{kT}{qV_D}} \tag{11}$$

For qV_D = 100 eV, at 300°K then $\sigma_y \sim 4.7$ μm or $\sigma_y/d \sim 0.016$. This implies that diffusion may be relevant to charge sharing between strips for small pitch detectors.

B. Noise In Front End Amplifiers

There are two general noise sources, thermal noise and shot noise[2)]. Per unit frequency interval dω the rms. noise currents are

$$i_T^2 = \frac{2kT}{\pi R} \, d\omega \tag{12}$$

$$i_s^2 = \frac{qI}{\pi} \, d\omega \tag{13}$$

Assume a source capacity C_s, source resistance R_s, and source charge drive Q_s. The front end amplifier has a gain A and time constant (low and high pass) of τ.

$$f(\omega) = A\left[\frac{\omega\tau}{1+(\omega\tau)^2}\right] \tag{14}$$

The amplifier inputs are characterized[3)] by thermal noise due to R_s, shot noise due to a standing current I_B and thermal noise due to input impedence $g_m = qI_E/kT = 1/R_B$ (see equation 3). Assuming currents sink into C_s and not R_s, the rms voltage noise is

$$\overline{v^2} = \overline{i_T^2}\, Z^2_{Cs} + \overline{i^2_s}\, Z^2_{Cs} + \overline{i^2_T} R^2_B \qquad 15)$$

$$= \left[\frac{2kT}{\pi R_s (\omega C_s)^2} + \frac{qI_B}{\pi(\omega C_s)^2} + \frac{2kT}{\pi g_m}\right] d\omega \qquad 16)$$

Convoluting $\overline{v^2}$ with $f(\omega)$ yields the noise sources modified by the amplifier.

$$\langle v^2 \rangle = \int_0^\infty |f(\omega)|^2 \overline{v^2} d\omega \qquad 17)$$

$$\langle v^2 \rangle = A^2 \left[\left(\frac{kT}{2R_s} + \frac{qI_B}{4}\right) \frac{\tau}{C_s^2} + \frac{kT}{2g_m \tau}\right] \qquad 18)$$

The voltage amplifier output due to the source charge will be $(Q_s A/C_s)e^{-1}$ where e^{-1} is due to $f(\omega)$ if the shaping is matched to t_c $(\tau \sim t_c)$. The definition of the equivalant noise charge, ENC, due to noise is $(A\ \mathrm{ENC}/C_s\ e)^2 = \langle v^2 \rangle$. The ENC is typically thought of as consisting of series and parallel parts which are folded in quadrature.

$$(\mathrm{ENCP})^2 = e^2 \left(\frac{kT}{2R_s} + \frac{qI_B}{4}\right) \tau \qquad 19)$$

$$(\mathrm{ENCS})^2 = e^2 \left(\frac{kT}{2g_m \tau}\right) C_s^{\ 2} \qquad 20)$$

The series noise is proportional to the source capacity. For low source capacity (as with silicon), ENC~ENCP. For example, Q_s~5.1 fC ~ 32,000 q. The ENCS due to g_m^{-1} ~ 25 Ω at 1 mA with $\tau = t_c$ ~ 10 nsec shaping and C_s ~ 30 pf stray capacity is 1125 q. Taking an input impedence of R_s = 1MΩ and base current of 1 μA, yields ENCP = 825 q. Thus the signal to noise is ~ $Q_s/\sqrt{ENCS^2+ENCP^2}$ = 23.

C. Detectors

Detectors have lately become commercially available from a variety of sources. There exists a variety of available pitches and fanout schemes. It appears that at Fermilab, Micron[4)] is as near to a standard as can be found. These detectors are used by E691 and E687, for example, as well as others.

It is assumed that the detector strips are fanned out to a connector. For example Micron design L is 5 cm x 5 cm with 688 channels mixed between 25μm and 50 μm pitch. The fanout is on Kapton to a receptacle 2.54 cm wide. The 1/10" centers of this receptacle are organized as 4 channels wide by 32 channels long. A typical card cage for this connector is shown in Figure 1. The design is that used in E-691 at Fermilab for the MSD2 preamp modified for the longer MSP1 thick film hybrid, which has identical pinouts.

D. Preamp

A great variety of preamps exists for silicon detectors. On the basis of some comparative tests, a preferred preamp[5)] was chosen. The dimensions are shown in Figure 2. This preamp, the CERN MSP1, is compatible with the detector and card cage shown previously. It too is available commercially.

The ENC is quoted to be ~ 1040 q for short gate widths (140 nsec) and C_s = 20 pf. The input impedance is 1K Ω, while the output is differential. The shaping time is ~ 70 nsec. Power dissipation is 55 mW/channel.

Bench tests of the MSP1 were made by injecting 8 nsec input pulses. Supply voltages were ±5V. The current gain (single ended into 50 Ω) was 1000. This gain is ~30 times that of the CERN MSD2 preamp. That means that an input signal of 100 nA (5 fC in 50 nsec) will give outputs of ±5 mV into 50 Ω. Such a signal is large enough that extensive RF shielding of the cable beyond the first preamp stage is unnecessary. The noise of the preamp is $\leq$ 10 nA referred to the input. The rise time is ~ 5 nsec. The output is bipolar up to 40 mV output.

The differential outputs of the MSP1 make it ideal for fanning out away from the congested SMD region. A schematic of a remote amplifier and discriminator is shown in Figure 3. Ordinary unshielded twist and flat cable is perfectly adequate as a fanout cable. For example, the Fermilab standard Nano N-277C could be used as the final amplifier and discriminator. The MSP1 is well matched to the ± 0.25 mV input threshold limit of this unit. In fact, the operation of this complete system was found to be quite painless.

E. Test Results

A test setup was constructed as shown in Figure 4. A Sr^{90} source was used to illuminate a 300 μm deep, 50 μm pitch Enertec SMD[6)]. The gate was provided by 2 plastic scintillators placed in coincidence. The defining counter had a width a=2.54 cm placed at a height h = 10 cm above the source. The maximum angle of incidence to the SMD is then ±127 mrad. Since the SMD is ~2.5 cm above the source, the number of strips illuminated is ~ (50 μm/25400 μm) 4=$(.008)^{-1}$.

The SMD amplifier chain simulates the standard readout scheme; an MSP1 preamp driving twist and flat cable terminated in a 733 amp followed by a discriminator set at threshold V_T. In figure 5 is shown the coincidence ratio S1.T/S1 for various bias voltages V_D. Full depletion appears to be achieved at ~ 60 volts bias. Hence, V_D was set to 100 volts.

Having set V_D for full depletion, one expects a charge collection time of $t_c \sim$ 9.0 nsec (for holes). In Figure 6 the coincidence ratio vs delay time is shown. A total timing jitter of 12 nsec is observed. This jitter is due to both phototube, SMD, and electronics. Clearly, the total jitter which is observed is such that > 25 nsec coincidence gates can be used if the SMD is to operate in a digital mode.

The singles rate of a strip is shown in Figure 7 as a function of V_T. The noise rate is an exponential function of V_T with a noise exponent V_T^n=5.65 mV. If one sets V_T = 100 mV then the rate is ~ 200 HZ/strip. For 1000 strips (5 cm wide, 50 μm pitch) the noise rate/plane would be 200 kHZ. With a 50 nsec gate width, the accidental probability/plane would be 1%. Adopting 200 mV as corresponding to 30,000 q then 5.65 mV means ENC ~ 850 q. This figure is roughly what is expected for this readout chain as mentioned above.

Finally, the pulse height spectrum gated on S=S1.S2 is shown in Figure 8. The exponential noise spectrum is clear in Fig. 8a which is a log plot. Clearly a usable signal appears, with a peak observable in the linear plot of Figure 8b. Note that charge sharing over strips has <u>not</u> been removed by the device of vetoing on hits in adjacent strips. Such a bias would be unrealistic since under experimental conditions the SMD will be uniformly illuminated.

<u>References</u>

1) a) Silicon Detectors for High Energy Physics, ed. T. Ferbel, Fermilab October 15-16, 1981

b) G. Charpak and F. Sauli, Ann. Rev. Nuc. Part. Sci. <u>34</u>, 285 (1984).

c) Vertex Detectors: Charm and Beauty I, Fermilab September 21-22, 1984.

2) The Art of Electronics, P. Horowitz and W. Hill, Cambridge University Press, 1980.

3) P. D'Angelo et al., Nuc. Inst. and Meth. <u>193</u>, 533 (1982).

4) Micron Semiconductor Inc., 126 Baywood Ave., Longwood, Florida (305)339-4365.

5) J.P. Avondo et. al., Nucl. Inst. and Meth. in Phys. Res. A241, 107 (1985).

6) Courtesy of E-691 (on loan).

Figure Captions

1) Card cage from E-691 (TPL) to hold preamps and connect to microstrip detector.

2) Dimensions and pinouts of the CERN MSP1 preamp.

3) Schematic layout of SMD, preamp, and amplifier/discriminator.

4) Layout of the system test.

5) Coincidence ratio vs SMD bias voltage for V_T=100 mV.

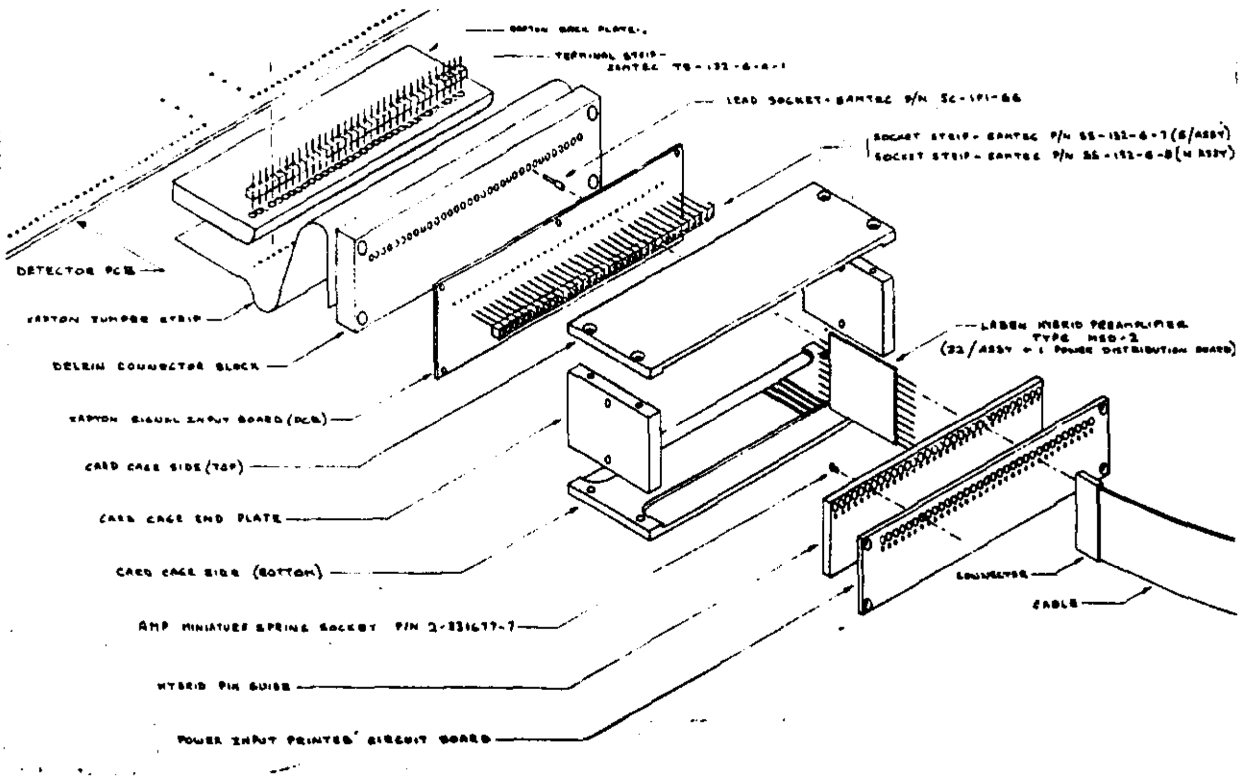
6) Coincidence ratio vs delay time for V_T=100 mV, V_D=100 V.

7) SMD singles rate/strip for various thresholds V_T.

8) Pulse height of detector with gate = S = $S_1.S_2$.

   a) Log plot showing exponential noise fallout with pulse height and the residual signal.

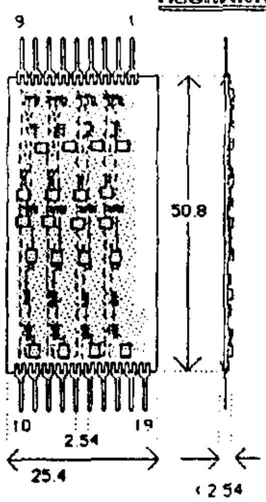
   b) Linear plot showing ~ 2:1 peak/valley.



DETECTOR PCB
KAPTON JUMPER STRIP
DELRIN CONNECTOR BLOCK
KAPTON SIGNAL INPUT BOARD (PCB)
CARD CAGE SIDE (TOP)
CARD CAGE END PLATE
CARD CAGE SIDE (BOTTOM)
AMP MINIATURE SPRING SOCKET P/N 2-331677-7
HYBRID PIN GUIDE
POWER INPUT PRINTED CIRCUIT BOARD
CONNECTOR
CABLE

Figure 1

MECHANICAL CONFIGURATION



1 - GROUND
2 - INPUT 1
3 - GROUND
4 - INPUT 2
5 - GROUND
6 - INPUT 3
7 - GROUND
8 - INPUT 4
9 - GROUND
10 - - Vcc (-6)
11 - NON INVERTING OUTPUT 4
12 - INVERTING OUTPUT 4
13 - NON INVERTING OUTPUT 3
14 - INVERTING OUTPUT 3
15 - NON INVERTING OUTPUT 2
16 - INVERTING OUTPUT 2
17 - NON INVERTING OUTPUT 1
18 - INVERTING OUTPUT 1
19 - + Vcc (+6)

BLOCK

DIAGRAM

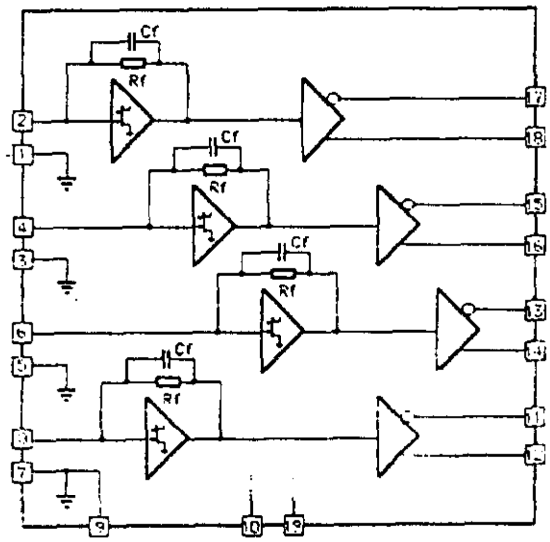


Figure 2

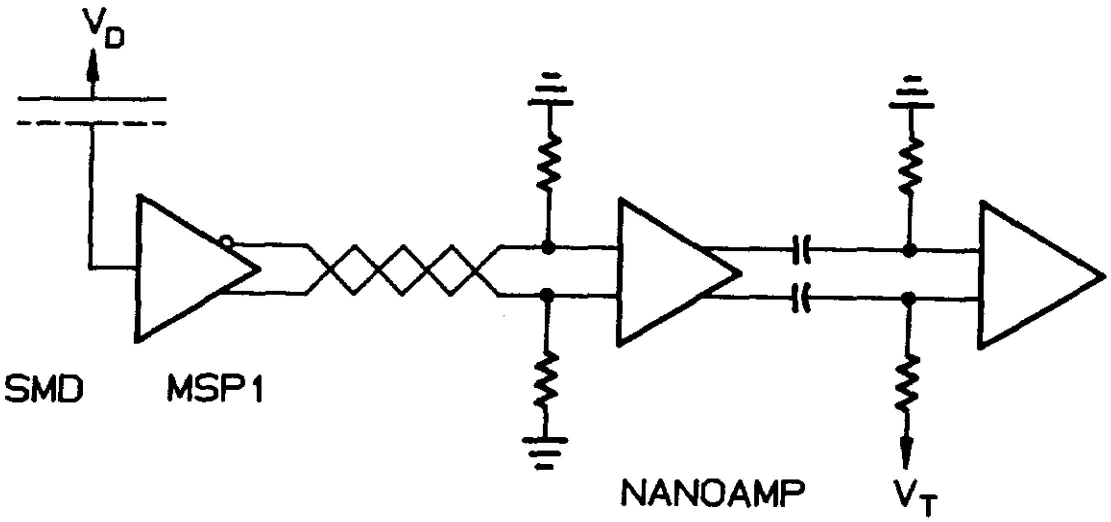


Figure 3

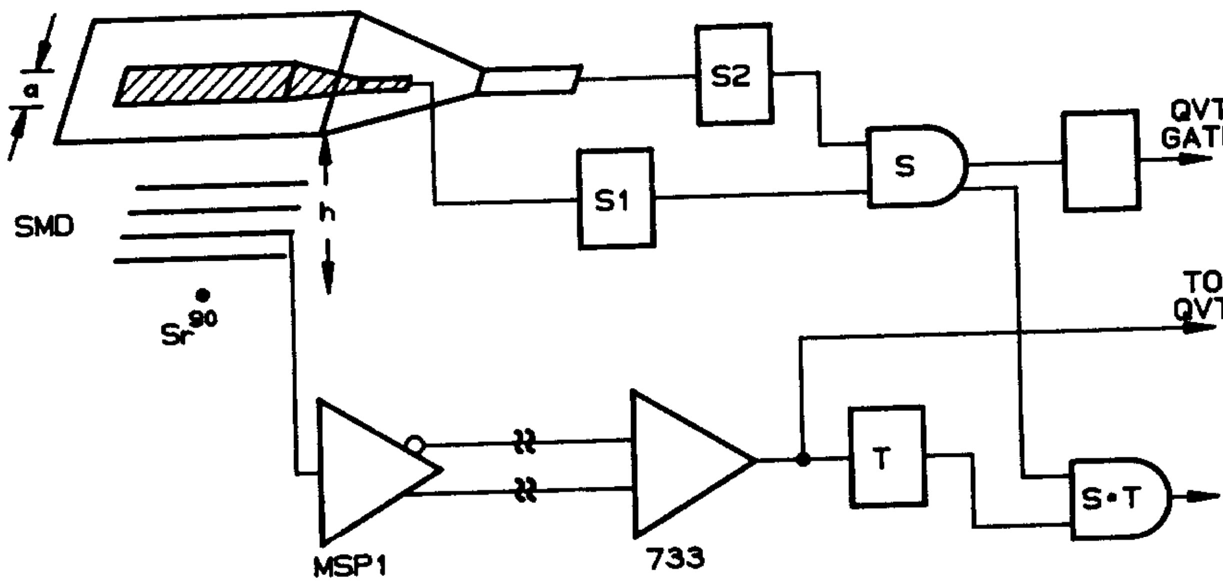


Figure 4

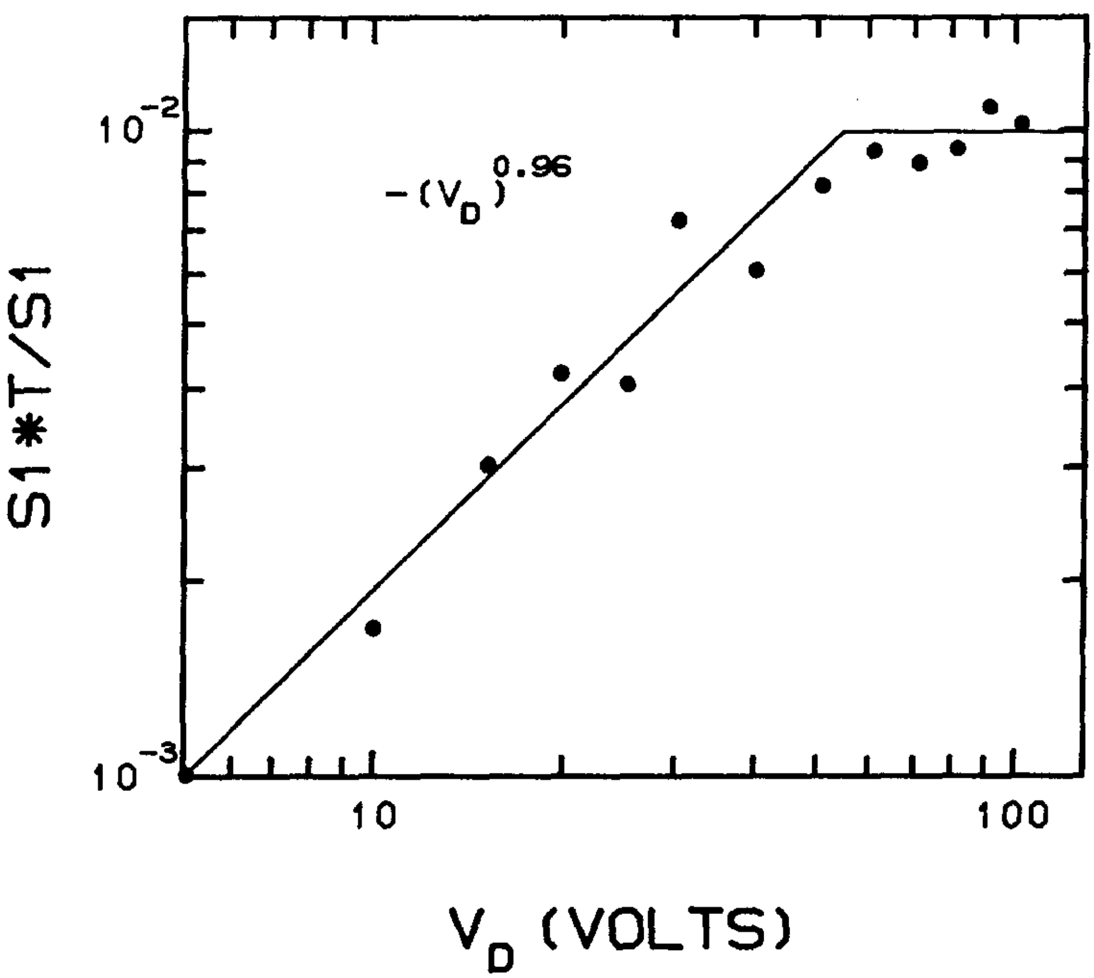


Figure 5

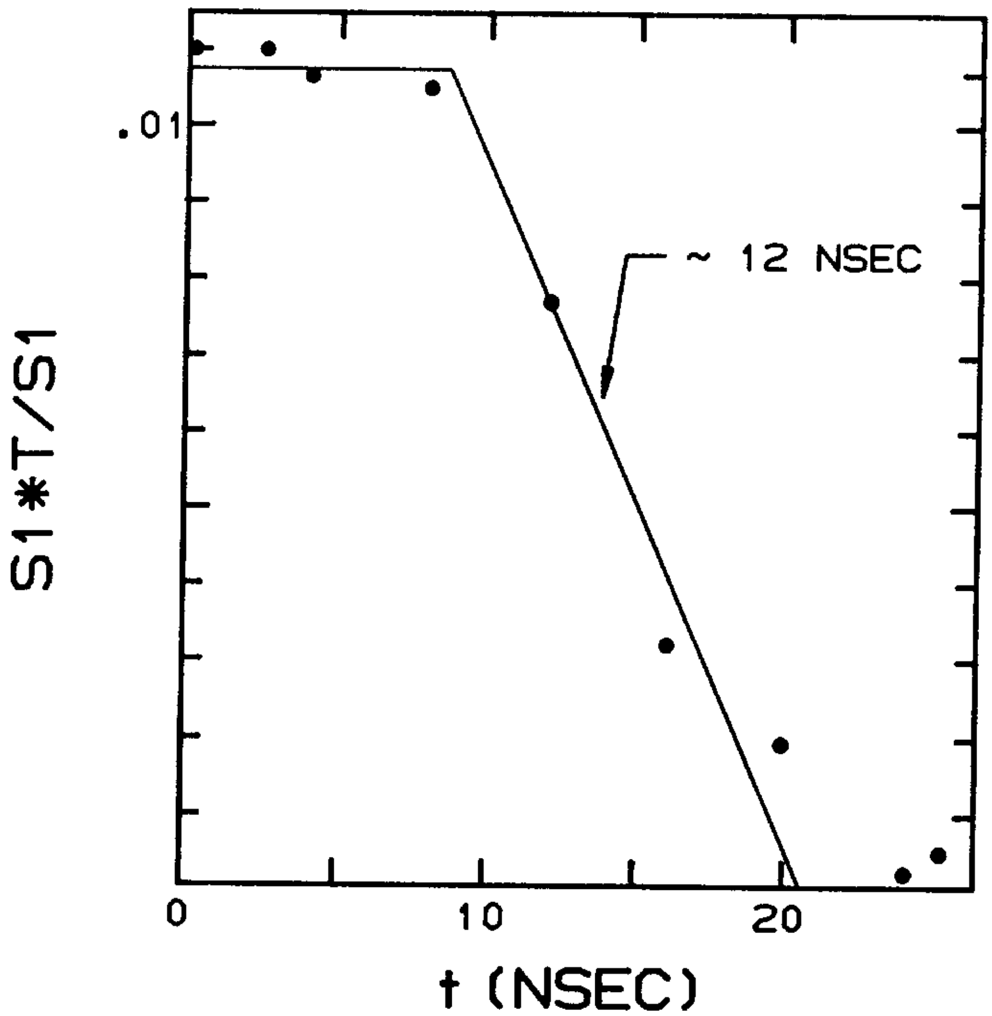


Figure 6

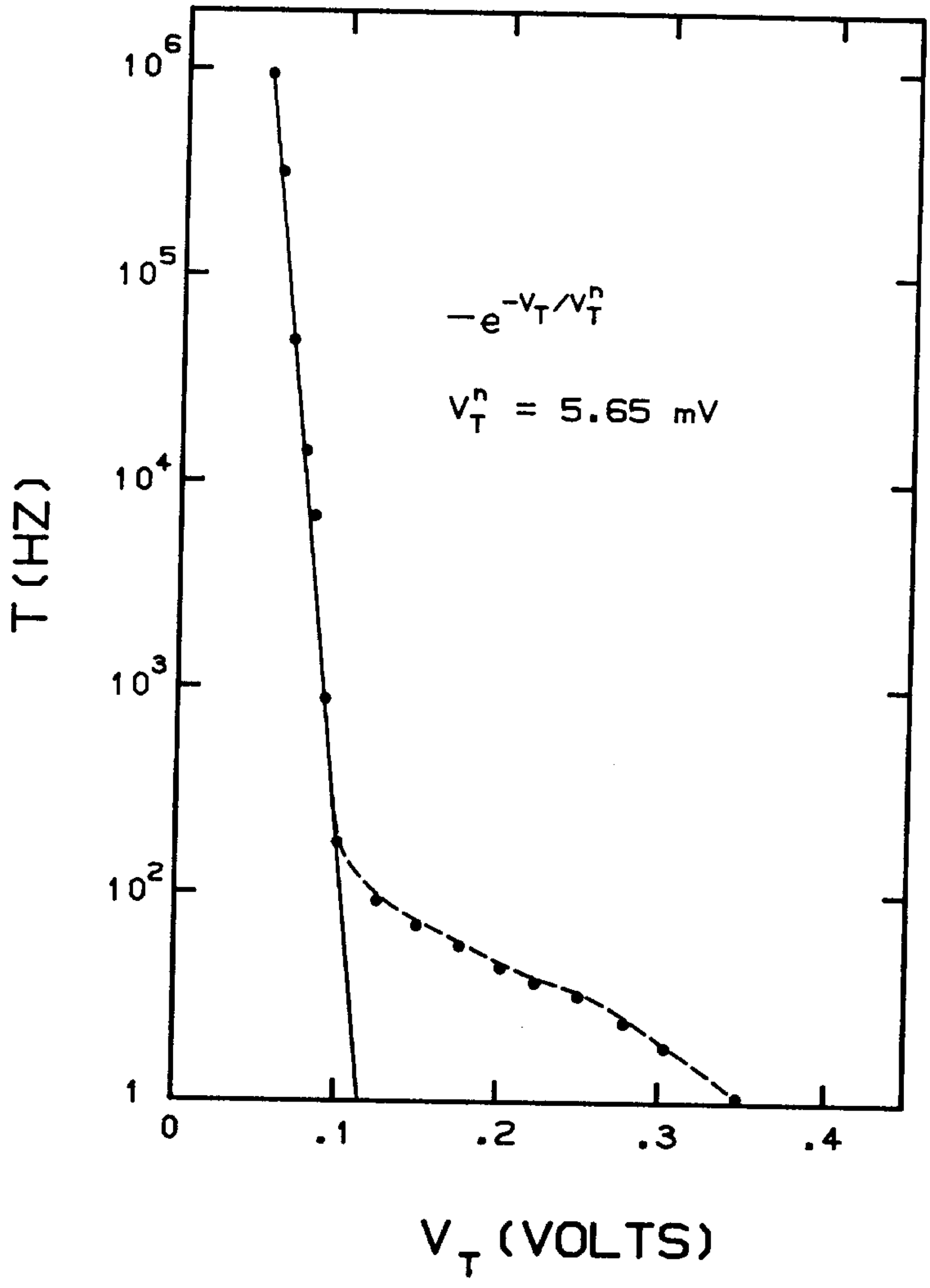
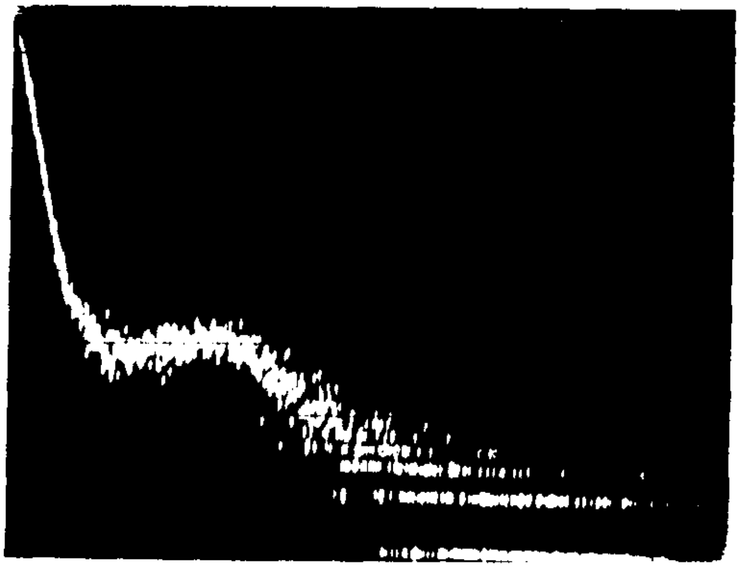
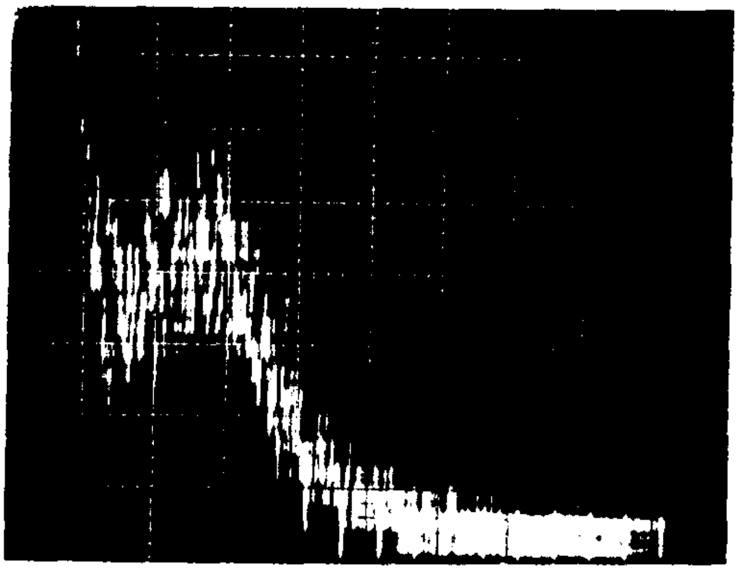


Figure 7



a)



b)

Figures 8a and 8b